SCIENCE FOR GLASS PRODUCTION

THE EFFECT OF MECHANICAL AGITATION ON CONVECTIVE HOMOGENIZATION OF GLASS MELT

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Experimental data are supplied on the specifics of glass melt flows in the beginning of the chilling part of the tank, behind the barrier, and in front of the working zone, when using agitators in industrial glass-melting furnaces. It is established that in order to eliminate coarse cords and layers, the velocity gradient of glass melt flows ought to be increased by 2 orders of magnitude, compared to the natural homogenization. This purpose can be accomplished most simply and efficiently through mechanical agitation of the glass melt.

The study of the process of homogenization in glass-melting furnaces [1 – 5] suggests that mechanical agitation of glass melt is an efficient instrument for improving its chemical homogeneity, since it intensifies the convective blending of the melt, which in general form depends on the gradient of the flow velocities and is determined by shear and tensile forces. This mechanism is discussed in sufficient detail in theory [6 – 10], whereas the scope of experimental studies in this area is yet extremely limited.

In this context, the purpose was to obtain data on the specifics of glass melt migration when using agitators in industrial glass melting furnaces. The melt flows were investigated in the beginning of the chilling zone, behind the barrier, and in front of the working zone.

The agitation in each variant was implemented by four impeller agitators made of chamotte, with blade diameter 0.5 m, height 0.2 m, and blade tilt 45° [3]. The studies were carried out employing floats by measuring the glass melt temperature in the site of stirring, in accordance with known methods.

The following factors affect the conditions of the glass melt homogenization: the rotational speed of the agitators, the depth L of their immersion in the glass melt, the clockwise or counterclockwise rotation of the agitators, the agitator diameter d, the blade height h, and the blade tilt angle β [1 – 3].

The experiments showed that the melt under the effect of the agitators' performance starts rotating around the agitator axis, and radial-axial migration occurs, which generates a certain volume of agitated glass melt named by the author

the "active volume" V_a. The cross-sectional area of the active volume S_a can be approximately expressed in the following form:

$$S_a = d_a \delta_a ,$$

where d_a and δ_a are the diameter and the thickness of the active volume.

The agitated glass melt is an obstacle in the way of the upper convective flows. The homogenization conditions in the chilling zone of the glassmelter can vary significantly, depending on the degree of the active effect of the agitators on the circulating flows generated by them and the surrounding longitudinal flows.

The measurements of the sizes of active agitated volumes indicate that their diameters are close to $2d$, which agrees with analogous observations made in optical glass melting. When active volumes are brought together to a distance equal to $a < 2d$ (Fig. 1a), this leads to the formation of a continuous zone of intense circulation, which the author named "the dynamic barrier."

The parameter that determines the complete mixing of the glass melt in the flow section S is the mutual arrangement of the active volumes with respect to each other. When the agitators are arranged in a row across the glass flow, two main variants of melt migration become possible. The first is $S \leq k S_a$ with $\delta_u \leq \delta_a$ (k is the number of agitators in the row; δ_u is the thickness of the upper convective glass melt flow). In this case, the cross section of the flow is fully overlapped by the sections of individual active volumes, and the glass melt arrives to the molding stage after having been thoroughly mixed. The second option is $S > k S_a$ with $\delta_u \leq \delta_a$.

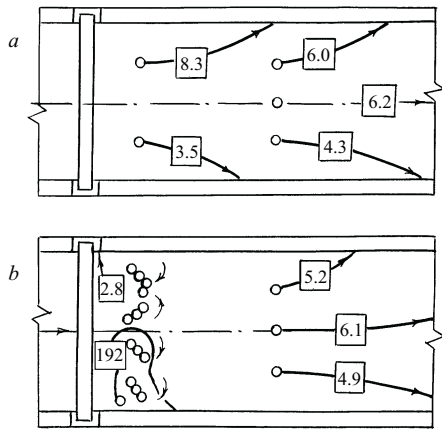[1] Saratov Institute of Glass Joint-Stock Company, Saratov, Russia.

Fig. 1. The effect of mechanical agitation of glass melt on the general scheme of convective flows in the chilling zone of the tank (framed numbers – flow velocities, m/h): *a*) standard conditions of furnace operation; *b*) agitation of glass melt beyond the barrier.
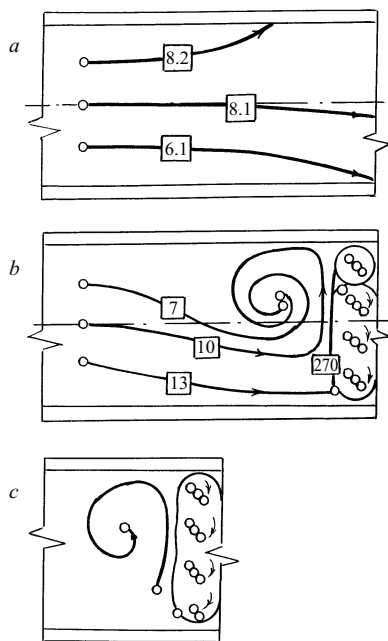

Fig. 2. The effect of mechanical agitation in front of the working zone on glass melt migration in the working channel (framed numbers – flow velocities, m/h): *a*) standard conditions of furnace operation; *b* and *c*) different variants of glass melt agitation.

Here the sections of individual active volumes do not overlap the section of the glass melt flow across the tank width. In this case a portion of unmixed melt may penetrate between the mixed melt flows. This situation arises when *a* exceeds 2*d*. Therefore, the number of agitators in the row should be $k \geq B/2d$ (*B* is the tank width in the agitation zone).

The present study established that when the agitators are placed in a row with the distance between them less than 2*d*, the active volumes deform each other, both toward the working zone and toward the melting zone. Depending on the ro-

tational speed of the agitators, the dynamic barrier width ranges from 2*d* to 3*d*.

The active volume of agitated glass melt in the dynamic barrier V_d for the mixing parameters specified in Figs. 1*b* and 2*b* can be described using the expression

$$V_d = 3dB\,(L + h\,).\qquad(1)$$

This is true for the cases when $L \leq 2h$. The expression $(L + h\,)$ indicates that when an agitator is immersed to the depth *L*, the glass melt layers beneath the agitator, whose total thickness is approximately equal to one blade height, become involved in the mixing process.

The study of glass melt flows indicated that the performance of agitators has but insignificant effect on the melt migration beyond the mixing zone. Within the mixing zone, the directions and speeds of melt flows are significantly modified. The speed becomes more than 30 times higher (Fig. 1). With the rotational speed of the agitators $0.15\ \text{sec}^{-1}$ and their immersion to 0.25 m, the average flow speed was 116 m/h: in front of the agitators it was 170 m/h, and beyond the agitators it was 60 m/h. At the same time, a cross-lateral flow of agitated glass melt is formed (the wavy curve in Fig. 2*a*), which limits the mixing zone and generates secondary flows inside the glass melt arriving to the mixing area (the spiral-shaped curves in Fig. 2*b* and *c*).

It is known that under normal conditions, the surface flows in the chilling zone diverge in a fan-shaped way toward the lateral walls, which indicates that glass melt arrived into the working channel from the central part of the chilling tank. While the agitators operate, the circular flows deform the longitudinal glass melt flow in front of the mixing zone (Fig. 2*b*) in such a way that, when the agitators start operating, the glass melt starts coming into the working channel from another part of the tank.

The determination of the surface flows speed in the chilling zone of the tank during the agitation makes it possible to estimate probable changes in the sheet glass laminated structure.

The available mathematical models of convective homogenization [8 – 10] distinguish two types of deformation: tensile deformation, when the glass melt flows accelerate, and shear deformation, in the case of viscous flowing of the melt. The degree of tensile deformation of cords was estimated through calculations. When inhomogeneities (layers or cords) enter the mixing area, the speed of glass melt migration increases, and the sectional surface area decreases. On the basis of the physical meaning of the above phenomenon, the following calculation formula can be proposed to determine the degree of their tension:

$$S_1 = S_0\,(v_0 / v_{\text{in}}\,),\qquad(2)$$

where $S_1 = \dfrac{\pi d_1^2}{4}$ is the cross-lateral surface area of the tensile

inhomogeneity d_1; $S_0 = \dfrac{\pi d_0^2}{4}$ is the cross-lateral surface area

of the initial inhomogeneity of diameter d_0 in front of the mixing zone; v_0 is the average speed of the glass melt flow, in which the inhomogeneity is moving; v_{in} is the average migration speed of the inhomogeneity in the mixing zone.

The calculation using expression (2) indicates that the inhomogeneity of diameter $d_0 = 5$ mm is transformed into an inhomogeneity of diameter $d_1 = 0.77$ mm, if the flow velocity under the effect of the agitators increases from $v_0 = 10$ m/h to $v_{in} = 268$ m/h. In some cases, such thinning of layers is sufficient to ensure good optical characteristics of glass [11].

The thinning of cords is also possible in standard glass-melting furnaces in the sites where glass melt flow accelerates, for instance, behind the quelpunkt. However, in accord with formula (2), is the speed of the upper convective flow is doubled, the inhomogeneity diameter is reduced to only 3.5 mm.

It is interesting to study the shear deformation of the inhomogeneity (Fig. 3). The alteration of the cord thickness is described according to Geffcken [8] by the expression

$$d = \frac{d_0}{\tau(\mathrm{grad}\, v)}, \qquad (3)$$

where τ is the duration of the presence of the inhomogeneity in the active volume of the agitated glass melt, sec.

The variations in the speed of migration of the floats in the agitation zone make it possible to calculate the velocity gradient from the formula:

$$\mathrm{grad}\, v = \frac{v_a - v_b}{l_{ab}},$$

where $\mathrm{grad}\, v$ is the velocity gradient, sec^{-1}; v_a and v_b are the maximum and the minimum flow velocities, m/h; l_{ab} is the distance between the glass melt layers, m.

In order to determine the probable time of the deformation of an inhomogeneity in the agitated glass melt volume, the following equation was obtained experimentally:

$$\tau = \frac{\rho V_d}{Ek}, \qquad (4)$$

where ρ is the glass density, kg/m^3; E is the furnace efficiency, taken equal to 1.25 kg/sec.

An assumption is made in the calculation that the linear velocity of the glass melt at the end of the blade is equal to the circular velocity of the blade edge.

It can be seen from Table 1 that the gradient of the glass melt flow velocities in stirring is by 2 orders of magnitude higher than the velocity gradient of the convective flows in the chilling zone of the furnace. In order to determine the thickness d_1 of an inhomogeneity deformed by the shear force, using equation (3), it is necessary to determine the time τ of its
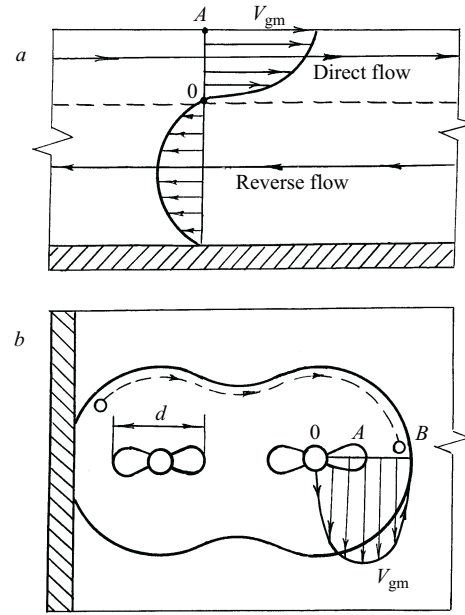

Fig. 3. Epures of glass melt flow velocities: a) in longitudinal convective flows, $v = 7$ m/h is the average velocity of the upper longitudinal flow in the chilling zone on the surface of the melt, $0A = 0.45$ m is the thickness of the upper flow, $---$ is the boundary between the upper and the lower convective flows; b) on the surface of the active volume of agitated glass melt, $v = 848$ m/h is the linear velocity of the blade edge, $AB = 0.3$ m is the distance between the blade edge and the boundary of the active volume of agitated glass melt, $d = 0.5$ m is the agitator diameter.

presence in the active volume V_d of agitated glass from expression (4); V_d, in turn, is calculated based on expression (1).

Knowing the limiting sizes of the dynamic barrier (Fig. 2): width $3d$, length B (equal to the width of the chilling zone $= 3.75$ m), depth $(L + h) = 0.5$ m (the depth is determined by studying temperature variations along the depth of the active melt volume), it is possible to calculate:

$$V_d = 3 \times 0.5 \times 3.75 \times 0.5 = 2.8 \ \mathrm{m}^3.$$

By substituting the value V_d into formula (4), we obtain $\tau = 1400$ sec. Next, using equation (3), we determine the final thickness of the inhomogeneity.

The calculations based on expression (3) indicated that as a consequence of the deformation of cords in the shear force field, their original thickness, for instance, $d_0 = 5$ mm,

TABLE 1

Measurement site	Flow velocity, m/h		Distance between glass melt layers, m	Gradient of flow velocities, sec
	minimum	maximum		
Upper convective layer in front of mixing zone	0	7	0.45	0.0043
Circulation flow in active mixing volume	116	848	0.35	0.58

decreases to $d_1 = 7$ μm, which well agrees with the known theoretical concepts [8].

These variations in the sizes of inhomogeneities is evidence of the high extent of their dispersion in the sheer force field generated by the agitators, and this is substantiated by studies of the laminar structure of sheet glass in glass melt stirring [1]. This in turn, means that forced homogenization of glass melt makes it possible to bring to completion its natural homogenization.

The results of the study demonstrated that in order to eliminate coarse cords and layers, the gradient of the glass melt flow velocities ought to be increased by 2 orders of magnitude, compared to natural homogenization. The simplest and most effective way to accomplish this purpose is mechanical agitation of the glass melt.

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